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Status Report of the DAΦNE Φ-Factory in Frascati

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Abstract

The DAΦNE Φ-Factory in Frascati [1] is a high luminosity, low energy collider. The high current beams circulate in two rings in multibunch configuration, crossing at horizontal angle, with equal horizontal and vertical design beam-beam tune shifts. After less than one year of commissioning the machine is now ready to accommodate the KLOE [2] and DEAR [3] experiments and start data taking in April '99. Luminosity tune-up has been carried out in the single bunch mode and a value of 10^{30} cm^{-2} s^{-1} has been exceeded. Shifts dedicated to multibunch operation in single ring mode have proved the reliability of the longitudinal feedback system. Multibunch collisions have also been tested. The status of the machine and luminosity measurements are presented.

1 Introduction

In order to obtain the high luminosity needed for a Φ-Factory, a high-current, multibunch approach, similar to that of the B-factories presently under commissioning (PEP-II, KEKB) has been adopted for DAΦNE. The two beams are stored in two separate rings and travel in the same vacuum chamber only in the two Interaction Regions (IR), crossing in two Interaction Points (IP) at a 25 mrad horizontal angle, in order to minimize the effect of parasitic crossings and to allow for a high collision frequency. The Phase I luminosity target is 10^{32} cm^{-2} s^{-1} with 30 bunches. A maximum of 120 bunches are foreseen for Phase II, with a design luminosity of about 5 10^{32} cm^{-2} s^{-1}. All the subsystems (vacuum, RF, injector and diagnostics) have been designed to cope

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Table 1
DAΦNE Design Parameters

Energy (Mev/beam)	510.
Single bunch luminosity ($cm^{-2}s^{-1}$)	4. 10^{30}
Trajectory length (m)	97.69
RF frequency (MHz)	368.26
Harmonic number	120
Natural emittance (m rad)	10^{-06}
Coupling factor	.01
Beta function @IP (H/V) (m)	4.5/.045
Particles/bunch	8.9 10^{10}
Bunch length (cm)	3
Natural relative energy spread	4. 10^{-04}
Damping times (L/T) (ms)	18/36

with a 5 A stored current. To operate with 120 bunches further investment on the longitudinal feedback and additional work on the cures of the parasitic crossings effects will be needed. The commissioning of the DAΦNE Φ-Factory without detectors ended last November, when the machine was shut down to allow for the installation of KLOE detector. KLOE is presently (March 99) being installed and operation with beam will resume next April for physics runs. The strategy of commissioning for Phase I aimed at tuning the machine for collisions and optimizing the single bunch luminosity before KLOE's installation, as a test of the machine capabilities. Single beam commissioning of the two rings, in single bunch mode, is completed: electron and positron currents larger than twice the design value (110 mA reached, 44 mA design) have been stored without instabilities and machine parameters have been measured and found in good agreement with the predictions of theoretical models. A machine coupling smaller than the design value has been obtained in both rings. Multibunch feedback systems have been also checked and currents of 0.54 A of electrons and 0.56 A of positrons have been stored, only limited by vacuum. A maximum single bunch luminosity of 1.6 10^{30} cm^{-2} s^{-1} has been so far obtained, while in multibunch collision, less extensively tested, a luminosity value of about 10^{31} cm^{-2} s^{-1} in a 13+13 bunches configuration has been achieved. In Table 1 the DAΦNE design parameters are reported.

2 Physics at DAΦNE

A high luminosity Φ-Factory is a unique tool to produce a very large number of $K_S K_L$ correlated pairs, suitable for studying CP and CPT violation in K decays. The KLOE detector has been designed for this purpose. Briefly, we mention some of the possible KLOE measurements:

- the measurement of the ϵ'/ϵ parameter, at the same statistical level of the next generation experiments at CERN and Fermilab, but with a different technique and with the advantage of having K_S and K_L decays detected in the same event. Furthermore, the measurement of $\mathrm{Re}(\epsilon'/\epsilon)$ and of any possible not zero $\mathrm{Im}(\epsilon'/\epsilon)$ - related to CPT violation - will be achieved with a very good accuracy looking at a unique feature: the correlation in the K_S, K_L decays;
- the detection for the first time of the expected CP violation in the $K_S \to \pi\pi\pi$ decay.
- Φ radiative decay [4] into the "mysterious" narrow mesons near 1 GeV, which have the same quantum numbers as the vacuum ones;
- structure functions and branching ratios of many K decay;
- $\gamma\gamma \to \pi\pi$ at very low pp invariant masses;
- Kaon interferometry and QM tests at a macroscopic scale;
- semi-rare K decays Form Factors.

By measuring the total hadronic cross section in the whole energy region allowed by DAΦNE, it will be possible to achieve:

- a precise measurement of the hadronic contribution to the anomalous magnetic moment of the muon;
- an accurate scan for other vector mesons.

A Φ-Factory is also suitable to study Λ-hypernuclei formation and decay. In fact, it has been demonstrated that very low energy K^- are the best probe for these processes and DAΦNE will be the most intense source available of low energy, monochro-matic K^-. Moreover, since K^- are produced in pairs with K^+, their detection will largely improve the measurements of hypernuclei decays. This study will be carried out by the experiment FINUDA [5], installed on the second Interaction Region after Phase II of commissioning. This high magnetic field detector (1.5 T) will also aim to solve the non mesonic Λ decay puzzle and the Δ I = 1/2 rule.

Before FINUDA installation a compact detector without magnetic field, DEAR, will run on the second IR in order to study exhotic nuclear physics: Kaonic atoms and the KN scattering length puzzle.

3 General Description

The DAΦNE accelerator complex consists of a ~ 60 m long full energy Linac, an intermediate damping ring, called Accumulator and two intersecting Main Rings. Transfer Lines, ~ 180 m long, connect the Linac to the Accumulator and the Accumulator to the Main Rings. The injector commissioning has been carried out in parallel with the main rings installation, for a total period of two months spread along two years. The Linac and Accumulator performance have exceeded the design values and both accelerators operate in a reliable way.

3.1 Injection System

The DAΦNE injection system has been sized to fill in few minutes the large required current in the Main Rings in the single bunch mode in order to ensure the maximum flexibility in the stored bunch patterns. The whole system runs at the operating energy of the collider, so that the current decay (mainly due to the Touschek effect) can be compensated by refilling the rings on top of the already circulating current. The LINAC is capable of accelerating electrons up to 740 MeV at 50 pps. In the positron mode of operation the first part of the LINAC (from the gun to the positron converter) is used to accelerate a 4A-10ns electron pulse at 250 MeV. Positrons are then accelerated up to 540 MeV by 10 accelerating sections. The design parameters have been achieved with both electrons and positrons and some of the parameter values are above specs. In particular, the current exceeds the nominal value by a factor of 2 for electron beam and by about a factor of 3 for positrons. The Accumulator has a compact 4 period structure, with a total length 1/3 of each ring and is used to store at 50 pps the required number of electrons (positrons) in one RF bucket and to damp the transverse and longitudinal emittance of the LINAC beam. The damped beam is extracted at ~ 1 pps and injected into a single bucket in the main rings. The maximum single bunch current stored under stable conditions exceeds 200 mA. The operation of the Accumulator for the collider commissioning is reliable and downtime negligible.

3.2 Main Rings

The ring periodic structure consists of four arcs (see Fig.1). The straight sections orthogonal to the IRs are used for injection, RF and feedback kickers. The arc cell, named BWB (Bending-Wiggler-Bending) [6], is quasi-achromatic, its special feature being the presence of a 1.8 T wiggler, 2 m long, in the region of maximum dispersion, which doubles up the synchrotron radiation emitted in the dipoles. The damping times are shortened and instabilities thresholds are raised. The wiggler allows also emittance tuning at constant field by appropriate control of the dispersion function. Moreover, the resulting increase of the natural energy fluctuation should raise the beam-beam tune shift limit. All quadrupoles and sextupoles are independently powered for maximum flexibility.

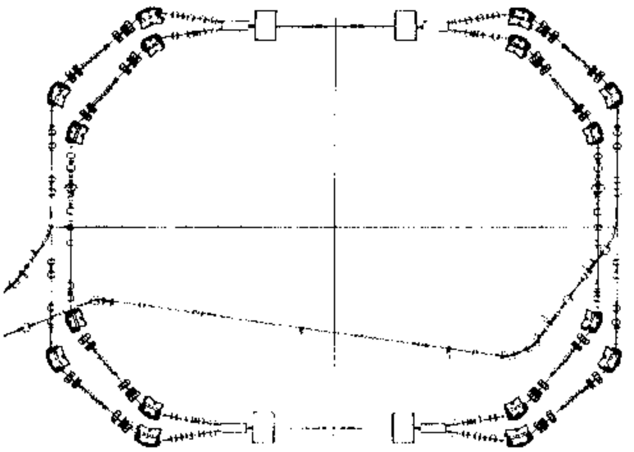

Fig. 1. *The Main Rings magnetic layout*

3.3 Interaction Regions

The IRs are a large fraction of the ring circumference (about 20%). The beams travel off-axis in the IRs, being separated at the IR ends by about 12 cm. To increase the separation and to lower the chromaticity, mainly due to the low-β insertions, a focusing sequence FDF has been chosen. For commissioning purposes two temporary IRs consisting of seven normal conducting quadrupoles, have been used to tune the optical functions, with one quadrupole placed at the Interaction Point (IP). A Beam Position Monitor (BPM) at the IP allowed to align the two beams for the colliding configuration. The first order IR transfer matrix and the β functions at the IP are the same as for the design KLOE IR, in order to match the same optical functions in the arcs, while the optical functions inside the IR and the quadrupole layouts are different.

The KLOE IR consists of 3 SmC permanent magnets low-β quadrupoles on each side of the IP, supported by the detector and immersed in the .6 T magnetic field of a 2.5 m radius superconducting solenoid. FINUDA IR will have 2 permanent magnets and 2 normal conducting quadrupoles immersed in the 1.1 T magnetic field.

Due to the low beam energy, the KLOE and FINUDA detector solenoids will be a strong perturbation to the machine optics (Bl = 2.4 Tm). The rotation of the beam is $\sim$ 45 degrees in the transverse plane and it is the main source of machine coupling. A compensation scheme, the Rotating Frame Method [7] has then been adopted to cancel this coupling. This scheme requires two compensating solenoids in a position symmetric to the main solenoid and a rotation of the low-β quadrupoles.

The KLOE beam pipe around the IP has to be as transparent as possible for the outcoming particles. In order to avoid K_S regeneration, it is required that the K_S decay before hitting the pipe. In order to have a large enough fiducial volume for the K_S, the cylindrical pipe around the IP is welded to a 500 mm thick sphere with a 10 cm radius. A 50 mm thick Be cylindrical shield is welded inside the sphere to provide RF continuity of the beam pipe. The chamber, made of a Be-Al alloy, is shown in Fig.2 before the insertion in the KLOE detector.

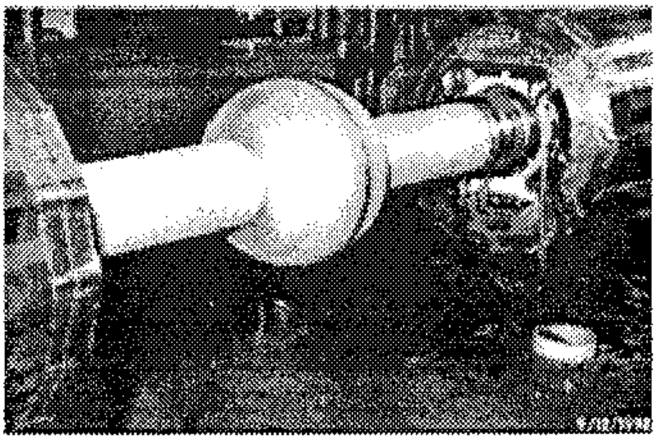

Fig. 2. *The KLOE pipe before insertion in the apparatus*

3.4 Subsystems

Special RF cavities, with low parasitic high order mode (HOM) content, have been developed to allow stable high current-multibunch operation [8]. The cavities, one per ring, are normal conducting copper single cells, with a system of HOM damping waveguides which couple out and dissipate the HOM energy induced by the beam on external 50 Ω loads. The HOM shunt impedance has been reduced by up to three orders of magnitude. No evidence of arcing or multipacting effects due to the loading waveguides has been observed and the performance of the damped cavities under high beam loading is quite satisfactory. A longitudinal bunch-by-bunch feedback system [9], implemented in collaboration with the SLAC/LBL PEP II group, is operational in both rings. It consists of a time domain system employing digital techniques. A damping time faster than 200 msec has been demonstrated in the positron ring with 30 bunches. The specially designed arc vacuum chambers [10] and the Ti sublimation pumps have been very effective and the static gas pressure in the arcs was in the 10^{-10} Torr range. At the moment no baking of the arc chambers is needed and further improvement of the vacuum is expected by beam conditioning of the vacuum chamber, very effective due to the high emission of synchrotron radiation. The vacuum in the day-one IRs was very poor since they were not baked, in view of replacing them with the final ones. The bad IR vacuum, specially under high beam loading, was a limit for high current operation. During the winter shutdown some operations to substantially improve the vacuum of the rings straight sections have been performed.

4 Single beam commissioning

4.1 Main Rings Optics

During the single ring commissioning β functions along the ring have been measured in each quadrupole and used for lattice modeling. The model takes into account the fringing fields of dipoles and quadrupoles (non negligible because of the short lengths and large apertures of the magnetic elements), all the focusing effects in the wigglers and the off-axis trajectory in the IR quadrupoles. The measured closed orbit before correction was inside the ring aperture in both rings. The sources of closed orbit are alignment errors, compensation of the trajectory in the wigglers and, since the two rings are very close, the stray fields from high field elements of the other ring. After closed orbit correction a coupling of the order of k ~ .002 has been obtained, much smaller than the design value (k = .01), also when sextupoles are turned on. Coupling has been estimated from the synchrotron light monitor and by the closest tune approach distance. The horizontal emittance measured by the

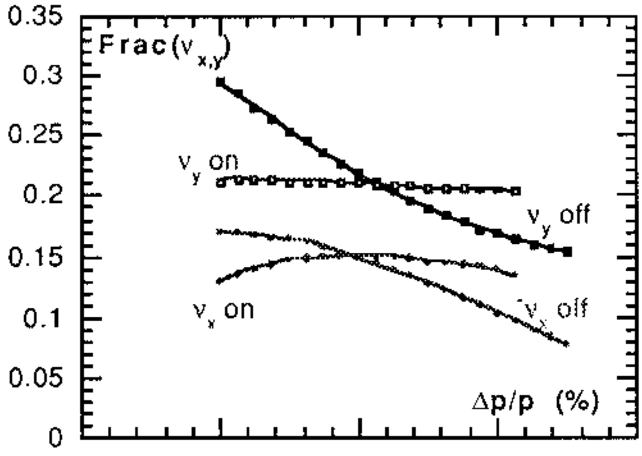

Fig. 3. *Betatron tunes vs relative energy deviation with sextupoles on and off*

synchrotron light monitor is in good agreement with the design value for both rings. The chromaticity has been measured and corrected using the same sextupole strengths in both rings and the behavior of the tunes versus the relative energy deviation, shown in Fig. 3 for the electron ring, is the same for both rings. The sextupole strengths have been tuned by powering only the eight sextupoles located in the arcs, arranged in four families, in order to improve the energy acceptance of the ring and therefore get a satisfactory beam lifetime.

4.2 Beam Dynamics

The maximum current stored in single bunch mode, 110 mA in both rings, largely exceeds the design value of 44 mA. The bunch length has been measured as a function of bunch current in the positron ring and found in very good agreement with numerical simulations based on machine impedance estimates [11]. According to these data the normalized coupling impedance $|Z/n|$ is below 0.6 Ohm. The transverse impedance is very low, as confirmed by the high threshold of the head-tail instability without sextupoles (13 mA in a single bunch). Ion trapping effects have been observed in the electron ring, due to the poor vacuum of the commissioning IRs, even in single bunch mode above 30 mA. Clearing electrodes [12] have been successfully tested. Although only partially powered, they helped in reducing the tune spread and shift due to the ions in the electron beam. In multibunch operation different filling configurations with a gap have been tested.

4.3 Multibunch operation

In the multibunch mode (all 120 bunches filled) 0.3 A in the positron beam and 0.23 A in the electron one have been stored without feedback. With the longitudinal feedback system on, up to 0.54 A of electrons have been stored in 25 bunches with a spacing of four RF buckets and an ion clearing gap of 5 consecutive bunches. With the positron beam 0.56 A have been stored in 30 uniformly spaced bunches. The uniformity of the stored current in the different bunches is quite satisfactory for both beams. These currents correspond to half the design value for 30 bunches and seem to be limited by vacuum and ion trapping.

5 Colliding beams commissioning

Maximum beam overlap is the preliminary condition to obtain high luminosity in a two rings collider. For this purpose a careful adjustment of the longitudinal timing and of the orbits at the IP has been performed. Fine tuning of the longitudinal overlap is performed by looking for the maximum counting rate of the luminosity monitor at high currents. The position in the IR is measured for each single beam in the same seven BPMs, canceling therefore any monitor offset. A BPM at the IP, installed for this purpose in the day-one IR, has been helpful during the initial set-up of orbit and timing for collisions. Closed orbit bumps in the IR with four correctors are used to adjust angle and displacement at the IP to equalize the orbit of the two beams in the vertical plane and set the crossing angle at the design value $\theta = 25$ mrad. Fine tuning of the vertical orbit is performed by changing the position at the IP in steps of 5 μm and looking for maximum luminosity monitor signal. Tuning the horizontal position and vertical angle is not necessary because the orbits are set with more than enough precision with respect to the beam size ($\sigma_x = 2.1$ mm) and to the angles inside the beam ($\sigma'_y = 0.47$ mrad). The beams were brought into collision in one IP only, while kept vertically separated in the other one. After the initial operation on the working point (5.11, 5.07) it was decided to run on the one (5.15, 5.21) farther from integer and sextupolar resonances. On this point the machine is less sensitive to closed orbit distortion, the dynamic aperture is larger and the lifetime longer. Beam-beam simulations [13] predict for this working point, with a single interaction point, a luminosity of 2.2 10^{30} cm^{-2} s^{-1} with a beam-beam tune shift parameter $\xi_{x,y}$ of 0.03 and good lifetime. During injection in collision mode the intensity of the injected beam saturated below the current of the already stored beam. The longitudi-

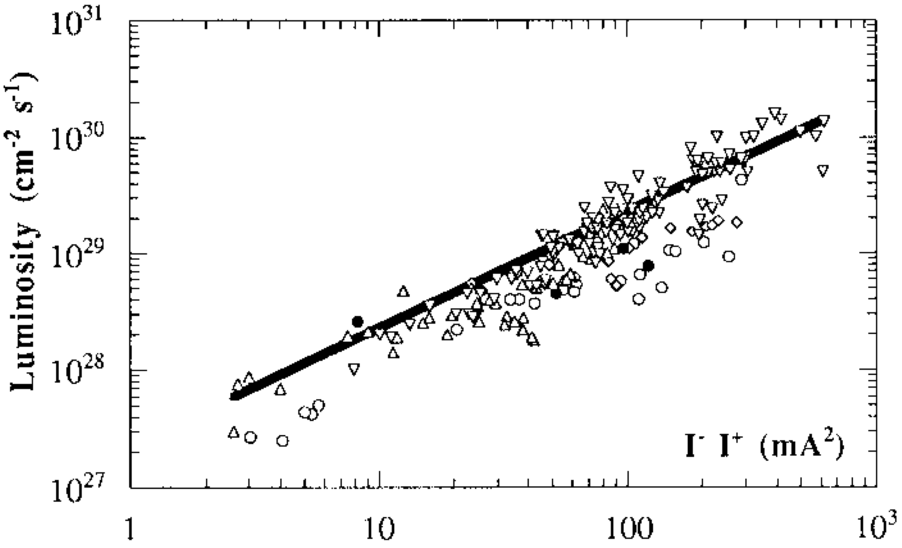

Fig. 4. *Single bunch luminosity vs. the product of e^+ and e^- currents*

nal and transverse oscillations of the bunch at injection cause crossings out of the nominal IP during a time comparable with the radiation damping one and produce particle losses. To overcome this limitation a "RF fast phase jump" procedure was implemented. Injection is made on non interacting buckets and then the RF phase of one beam is rapidly shifted towards the collision phase. If the phase shift is performed with a fast ramp (~ 600 msec) the bunch follows the RF phase. This procedure proved to work also in multibunch mode, shifting by two buckets 400 mA in 30 bunches without any beam loss. The single bunch luminosity measurements are shown in Fig. 4 as a function of the product of the electron and positron currents; the line represents the luminosity calculated with the design parameters for the same currents. After careful tuning of the collision parameters the measured luminosity turned out to be in good agreement with predictions, showing that a good beam overlap and a vertical beam size as low as the design value have been achieved. The maximum single bunch luminosity ($1.6\ 10^{30}$ $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$) has been obtained with $I^+ = 19$ mA, $I^- = 21$ mA (assuming equal tune shifts for the two beams this corresponds to $\xi_y \sim .03$). This is in good agreement with the predictions of beam-beam simulations with one IP on this working point.
Only two days were dedicated to multibunch luminosity measurements. Using the RF fast phase jump procedure a luminosity of the order of 10^{31} $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ has been obtained with 13+13 bunches. A short time has also been dedicated to luminosity measurements with two interaction points. In this case there is a luminosity degradation (~ 40%) in agreement with simulations. Since the lattice is asymmetric with respect to the IP, the beam experiences different phase advances going from IP1 to IP2 and back. The beam-beam behavior depends on the machine tunes but also on the phase advance difference between the two IPs. In the future, luminosity measurements with two IPs will be done on the optimum value of the phase advance difference predicted by the simulations.

6 Conclusions

The commissioning of the DAΦNE Φ-Factory in single beam mode without detectors is concluded. The colliding beams results obtained sofar have been described. In the next week the KLOE installation will be completed and the cool down of the solenoid will begin. Physics runs are expected to start in the middle of April 99.

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